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Production of Sweet Sorghum Bio-Feedstock on Technosol Using Municipal Sewage Sludge Treated with Flocculant, in Ukraine

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Abstract: This paper presents the influence of sewage sludge (SS) on the biometric parameters, absorption of mineral elements and thermal characteristics of sweet sorghum (*Sorghum bicolor* L.) grown on Technosol. Two types of sewage sludge were used: unmodified and modified with DAMET flocculant. Each type of sludge was applied in three doses (expressed as dry matter basis, DM): 20 t DM/ha, 40 t DM/ha and 60 t DM/ha, respectively. The yield of fresh biomass depended on the dose of sewage sludge: it increased by 14.5–41% and reached 104.6 t/ha after application of the sewage sludge with flocculant at a maximum rate of 60 t/ha. Sorghum biomass actively absorbs nutrients from the soil. Nitrogen was absorbed more actively; depending on the type and dose of sewage sludge application, its content in biomass increased from 12–40% (dose of 20 t/ha) to 80–112% (dose of 60 t/ha). By content in sorghum biomass, essential elements can be arranged in descending order as follows: Fe → Mn → Zn → Cu. Sorghum shows a low ability to accumulate some heavy metals in aboveground biomass. Despite the fact that large doses of sewage sludge contributed to an increase in the content of nickel, cadmium and lead in the substrate by 1.8–5.6 times, the ratio of the content of these elements in plants to the content in the substrate remained low. Sewage sludge affects the process of thermal degradation of sorghum biomass. The decomposition of the main components occurs at lower temperatures, and, as a rule, at higher rates. Sewage sludge (especially with flocculant) contributes to a more complete combustion of biomass. The results showed that sewage sludge with flocculant at a dose of 40 t/ha is the most optimal fertilizer option for growing sweet sorghum on such Technosols as loess-like loam.

Keywords: energy crop; biosolid; loess-like loam; biomass yield; macro- and micronutrients; heavy metals; thermal process

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1. Introduction

With increasing energy consumption from renewable sources, sewage sludge (SS) is increasingly seen as a promising fertilizer for energy crops [1–3]. Due to the fact that sewage sludge contains large amounts of organic and inorganic nutrients, it can complement or replace chemical fertilizers [4–6].

Field experiments on plots cultivated with sweet sorghum and fertilized with sewage sludge and solid digestate (a stabilized solid material obtained in biogas plants via anaerobic digestion of organic waste) showed a decrease in equivalent CO_2 emissions by 14 and 11%, respectively [7,8]. Meanwhile, the presence of potentially toxic metals in its composition often limits its use in agriculture [9–11].

The characteristics of sewage sludge depend on the quality of wastewater and the type of processes used for wastewater treatment. Sewage sludge is a heterogeneous material, being a mixture of microorganisms and non-biodegradable organic substances, consisting mainly of water and a small number of solids [12]. Sludge pretreatment includes thermal, mechanical, chemical and biological processes [13,14]. At this time, the traditional way of disposal of sewage sludge in countries such as Serbia, Malta and Ukraine is accumulation on special sites [15,16]. The low level of sewage sludge utilization in Ukraine is mainly due to imperfect legislation and outdated equipment and technologies for wastewater treatment [17,18]. According to the state standard of Ukraine (DSTU 7369:2013), municipal sewage sludge (MSS) can be applied to arable lands with minimum rates of 10 t/ha for three consecutive years. The permissible dose of sewage sludge is calculated according to the content of heavy metals in the biosolids. A larger dose of sewage sludge is accepted only in the case of land reclamation, taking into account the environmental risks.

Physical, chemical and biological pretreatments are often applied to enhance sludge filtration and the efficiency of final dewatering [19–21]. The differences in sludge pretreatment methods for sludge dewatering can affect its performance on agriculture lands [22].

Primary sewage sludge is produced after several wastewater treatment operations, including screening, grit removal, sedimentation, filtration, coagulation and flotation [23,24]. Waste activated sludge (WAS), or secondary sludge, is produced during secondary wastewater treatment and involves the activity of microbial biomass.

In Ukraine, sludge management is limited to storage in drying beds on the territory of the wastewater treatment plant or its transfer to landfills [25]. Several case studies connected with aerobic and anaerobic pretreatments of sewage sludge were developed at the regional level within scientific approbation in Ukraine [26–28].

The use of organic flocculants with high molecular weight is one way to improve the existing wastewater and sewage sludge treatment technologies [29–31]. These organic substances differ depending on their charge characteristics, ionic properties, special functional groups and molecular weight [32,33]. The aggregation of fine and colloidal particles, the formation of large flakes with the rupture of solvate shells and a change in the forms of water bonding occur during flocculation [34,35]. This leads to a change in the structure of the sediment and an improvement in its water-releasing properties [36].

The presence of potentially toxic metals often limits the use of sewage sludge in agricultural production [37,38]. Meanwhile, its valorization on the plantations of energy crops is quite justified, even more so on unproductive marginal lands [39,40].

The management of sewage sludge produced from municipal wastewater treatment plants is one of the critical issues facing modern society, due to the very fast increase in sludge production as a result of extended sewerage, new work installations and up-grading of existing facilities [41]. The application of sewage sludge on agricultural soils increases the content of organic matter, carbon and nitrogen;; increases porosity; and improves soil moisture capacity. Concentrations of Cu and Zn in industrial hemp parts (roots, stems and leaves) are significantly affected by soil physico-chemical parameters and especially by soil pH [42]. In alkaline soil, the mobility was lower and the movement towards the leaves was due to the increase in irrigation water level.

The biomass used for bioenergy generation mostly comes from agricultural crops grown for food consumption. In order to limit the concerns related to the reduction of the areas devoted to the cultivation of agricultural crops in favor of energy crops, the growers of energy crops have begun to turn their attention to marginal lands, namely degraded lands in terms of their physical/chemical properties, on which low yields or low-quality agricultural crops are obtained. Although marginal lands are less productive, their use for bioenergy crops also has secondary benefits, such as: improving soil properties, restoring degraded vegetation, carbon capture and other environmental benefits. Irrigation of marginal lands with wastewater, or amendment with sewage sludge, brings an important supply of nutrients to the soil.

Sweet sorghum is one of the promising annual energy crops that can be successfully grown on marginal lands [43–47]. Undemanding soil conditions, as well as high water use efficiency, are some important advantages of sorghum compared with other energy crops in arid climates [48–51]. It is advisable to use various types of fertilizers to increase the yield of sorghum on marginal or unproductive lands. There is evidence of the successful use of sewage sludge in the cultivation of sorghum on various types of marginal lands [52]. It has been established that sewage sludge application triggers a number of processes that directly affect the qualitative characteristics of the soil, and indirectly affect the characteristics of biomass [53,54]. Further research on the safe application of sewage sludge is necessary given the complexity of these processes [55].

The objective of this research was to study the effects of flocculant treatment of sewage sludge and sewage sludge application doses on sweet sorghum productivity, the intensity of various macro- and microelement accumulation and the thermal characteristics of sorghum biomass.

2. Materials and Methods

Field experiments were conducted in Ukraine, in the South of Dnipropetrovsk province, at the Pokrov Research and Educational Station of the Dnipro State Agrarian and Economical University (47°39′ N, 34°08′ E), with an elevation of 60 m. This site was founded at the top of a heap created after earlier-made mining operations for biological land reclamation [56]. This region is quite arid, and the annual rainfall is 465 mm. Physical annual potential evaporation reaches 700 mm, and the groundwater level is found at a depth of 20 m. The high distance between the top of the reclaimed heap and the groundwater level is up to 80 m, and prevailing evaporation of precipitation excludes the risks of groundwater pollution with the leaching of nitrates or mobile phosphates.

The sweet sorghum hybrid Medovyi F1 was bred by the Breeding and Genetic Institute—the National Center for Seed Production and Variety Research of the Ukrainian Academy of Sciences and recommended for cultivation in arid conditions of the steppe zone. This hybrid is a mid-early fodder crop and has a high sugar and fiber content.

The substrate for sweet sorghum growing was loess-like loam (Technosol) brought to the surface during the extraction of manganese ore and which underwent the process of long-term phytomelioration. The physical and chemical properties of the "young soils" are changing [57].

DAMET polymer was used as a flocculant in the final stage of wastewater treatment. The experiments included two types of activated sewage sludge application: (a) without flocculant treatment (SS), and with flocculant treatment (SS + F), respectively.

Sewage sludge with flocculant was characterized by a higher content of organic matter and nitrogen, and a lower content of heavy metals (Table 1).

The field experiment on biosolid testing was arranged with two factors, i.e., flocculant treatments (without and with flocculant) and dry matter doses (20, 40 and 60 t/ha). The sewage sludge was incorporated into the topsoil in the autumn of 2019, using reduced tillage (disking to 10–12 cm).

In the spring of 2020, cultivation was made before sowing. Seeds of sweet sorghum were sown in mid-May at a distance of 0.7 m between rows and 0.07 m within rows. The density of seeds was adopted so that the optimal density of plants at the time of harvesting was 12–15 plants/m^2. This is achieved at a seeding rate of 15–20 germinating seeds per 1 m^2.

Soil samples were taken after one month of incorporation into the topsoil (at 0–10 cm), dried and sieved (2 mm) for analytical purposes.

Parameters including the humus content; mass fractions of carbon, nitrogen, phosphorus and potassium; and the content of trace elements were determined in the loess-like loam using ordinary methods [58].

Table 1. Characteristics of sewage sludge.

Parameter	Content	
	Sewage Sludge	**Sewage Sludge with Flocculant**
Mass fraction of moisture (%)	15.99 ± 0.27	29.12 ± 0.31
Mass fraction of dry matter (%)	84.01 ± 0.41	70.88 ± 0.39
Mass fraction of ash (%)	50.75 ± 0.36	30.25 ± 0.28
Mass fraction of organic matter (%)	49.25 ± 0.31	69.75 ± 0.86
Mass fraction of total carbon, C (g/kg)	222.0 ± 2.19	354.0 ± 4.57
Mass fraction of total nitrogen, N (g/kg)	26.6 ± 0.28	38.6 ± 0.47
Mass fraction of total phosphorus, P_2O_5 (g/kg)	26.2 ± 0.27	12.0 ± 0.21
Mass fraction of total potassium, K_2O (g/kg)	4.3 ± 0.10	4.1 ± 0.09
Mass fraction of copper, Cu (mg/kg)	195.2 ± 1.92	98.6 ± 0.53
Mass fraction of iron, Fe (mg/kg)	20,019.5 ± 18.44	17,535.4 ± 16.86
Mass fraction of manganese, Mn (mg/kg)	420.0 ± 3.51	125.1 ± 2.52
Mass fraction of zinc, Zn (mg/kg)	875.9 ± 9.82	557.5 ± 7.39
Mass fraction of cobalt, Co (mg/kg)	3.0 ± 0.11	2.5 ± 0.08
Mass fraction of nickel, Ni (mg/kg)	4.7 ± 0.15	4.0 ± 0.09
Mass fraction of lead, Pb (mg/kg)	2.1 ± 0.08	1.5 ± 0.06
Mass fraction of chromium, Cr (mg/kg)	3.5 ± 0.09	2.2 ± 0.08
Mass fraction of cadmium, Cd (mg/kg)	1.4 ± 0.05	1.3 ± 0.05
Ratio C:N	8.3	9.2
pH	6.6 ± 0.13	6.6 ± 0.14

The following characteristics of sorghum have been studied: fresh biomass and grain yield, conservative sugar and theoretical ethanol production, macronutrients and trace elements content in above-ground biomass, thermal behavior of bagasse during combustion.

Plant sampling was made two times. The first time, fresh biomass at the wax stage was taken from the 1 m^2 plot and weighed in three repetitions. Grain mass was taken at the full wax stage from the 1 m^2 plot and weighed in three repetitions as well. Fresh biomass was weighed. The dry matter level was determined by fresh biomass drying at 60 °C for 24 h. The yield of ripe grain was determined by weighing it after threshing with subsequent conversion to t/ha.

The yield of conservative sugars was calculated based on an approach of assuming that the sugar concentration was 75% of Brix expressed in g/kg sugar juice.

The yield of conservative sugar was obtained with the formula:

$$CSY = (FSY - DSY) \times Brix \times 0.75$$

where CSY is conservative sugar yield ($Mg \cdot ha^{-1}$), FSY is fresh stalk yield ($Mg \cdot ha^{-1}$) and DSY is dry stalk yield ($Mg \cdot ha^{-1}$).

Theoretical ethanol yield was calculated as sugar yield multiplied by a conversion factor: 0.58 L ethanol per kg of sugar [59].

Total nitrogen, phosphorus and potassium analysis of plant material was made using a single digestion [60]. In order to determine the content of trace elements, plant samples weighting 2 g each were combusted in a muffle furnace at 450 °C, and then dissolved in 5 mL of 6N spectral purity hydrochloric acid. The prepared samples were analyzed with an atomic absorption spectrophotometer Saturn-3 (Ukraine).

Thermogravimetric analysis was used to study the calorific value of sorghum biomass. Samples of biomass were analyzed on a derivatograph Q-1500D (Paulik-Erdey, Budapest, Hungary) in dynamics at a heating rate of 10 °C/min in an air atmosphere. Differential mass loss, peaks of destruction and heating effects were recorded.

The data were processed with statistical methods using the software package StatGraphics Plus5 with significance level $p < 0.05$.

3. Results

The analysis of the content of organic matter and macroelements in phytomeliorated loess-like loam showed that the fertility of this Technosol is very low: the humus content was 1.19% (Table 2).

Table 2. Characteristics of loess-like loam.

Characteristic		SS			SS + F		
	Control	20 t/ha	40 t/ha	60 t/ha	20 t/ha	40 t/ha	60 t/ha
Humus (%)	1.19 ± 0.03	1.71 ± 0.06	1.86 ± 0.08	1.96 ± 0.08	1.60 ± 0.07	1.66 ± 0.06	2.14 ± 0.08
Mass fraction of dry matter (%)	96.6 ± 2.10	96.7 ± 1.90	96.9 ± 2.61	96.8 ± 2.5	97.2 ± 1.80	97.2 ± 1.87	97.0 ± 2.12
Total carbon (%)	0.69 ± 0.04	0.99 ± 0.06	1.08 ± 0.08	1.14 ± 0.09	0.93 ± 0.06	0.96 ± 0.05	1.24 ± 0.09
Mass fraction of nitrogen (mg/kg)	65.1 ± 1.80	80.0 ± 2.32	90.9 ± 2.48	103.8 ± 3.1	80.2 ± 2.30	92.2 ± 2.71	111.0 ± 3.60
Mass fraction of mobile phosphorus, P_2O_5 (mg/kg)	42.2 ± 1.31	160.1 ± 2.61	188.1 ± 2.90	214.2 ± 3.1	139.0 ± 2.11	176.1 ± 2.60	225.7 ± 2.81
Mass fraction of exchangeable potassium, K_2O (mg/kg)	206.5 ± 1.89	220.0 ± 2.50	226.6 ± 2.71	370.8 ± 3.8	227.2 ± 2.30	247.8 ± 2.52	350.2 ± 3.50

The application of sewage sludge increased the humus content up to 2.1%. The content of available nitrogen in the phytomeliorated substrate was low, not exceeding 100 mg/kg. The introduction of a simple sewage sludge contributed to an increase in the mass fraction of nitrogen by 22.9–59.5%, depending on the dose. The effect of sewage sludge with flocculant was slightly higher, namely 23.0–70.5%. Despite this, loess-like loam remains a substrate with a low nitrogen content, not exceeding 150 mg/kg. According to the content of exchangeable potassium, loess-like loam can be attributed to a substrate with an average supply of this element (within 200–300 mg/kg). The content of potassium increased to the highest values of 350–370 mg/kg in areas where sewage sludge was applied at a dose of 60 t/ha. Loess-like loam is a substrate with a high content of mobile phosphorus (42.2 mg/kg). The application of sewage sludge contributed to the additional entry of this element into the substrate. As a result, its content increased by 3–5 times, reaching maximum values in the SS trials (60 t/ha) and SS + F trials (60 t/ha), respectively.

Thus, there is some imbalance in the provision of loess-like loam with the main nutrients: a very low content of organic matter and nitrogen and an increased content of mobile phosphorus and exchangeable potassium. This conclusion is valid both for the control plot and for the options with the introduction of sewage sludge.

According to our previous studies [61,62], depending on weather conditions and substrate, the yield of fresh sweet sorghum biomass varies from 61 to 82 t/ha. In our experiments, the biomass yield on loess-like loam was 74.2 ± 0.7 t/ha. The introduction of sewage sludge contributed to an increase in plant height, biomass productivity and grain yield. The increase in growth rates was relatively small, ranging from 4% (SS 20 t/ha) to 18% (SS + F 60 t/ha). The increase in biomass was more significant, especially under the action of a dose of 60 t/ha, where the yield in the SS trial increased by 14.5%, and that in the SS + F treatment increased by 41% (Figure 1).

The application of sewage sludge also affected the yield of sorghum grains. The productivity increased from 6–15% (at a dose of 20 t/ha) to 34–60% (at a dose of 60 t/ha) (Figure 2).

As a result, grain yield increased from 7.1 t/ha in the control test to 9.5 t/ha (SS) and to 11.4 t/ha (SS + F). The largest increase in both vegetative biomass and grain was observed in the trials applying sewage sludge with a flocculant.

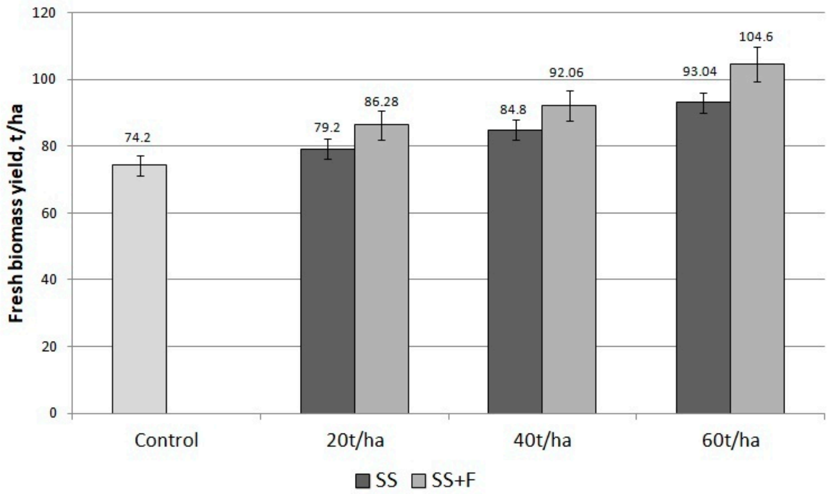

Figure 1. Yield of fresh sweet sorghum biomass: SS is sewage sludge; SS=F is sewage sludge treated with flocculant.

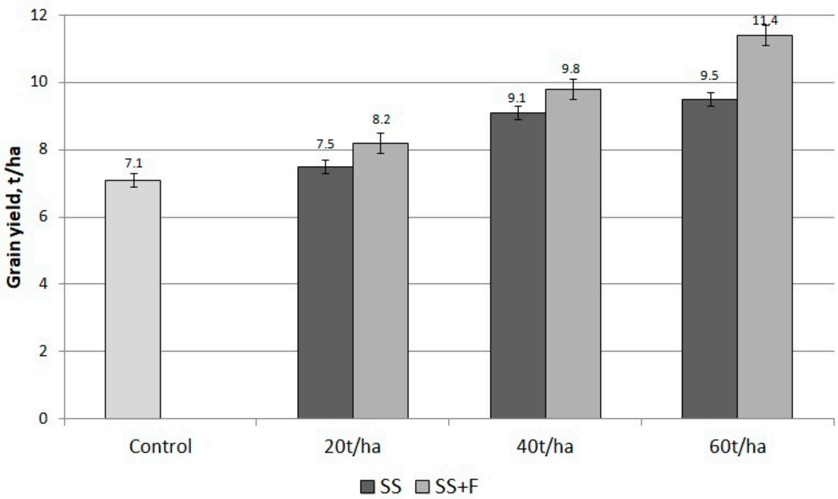

Figure 2. Sweet sorghum grain yield.

The yield of conservative sugar and theoretical ethanol based on biomass productivity and sugar content in sweet sorghum juice (19.1–19.3%) was calculated. The yield of conservative sugar of the sweet sorghum hybrid Medove can vary in different years within 4350–5900 kg/ha, and that of theoretical ethanol from 2550 to 3450 L/ha [42].

The yield of conservative sugar in the treatment without fertilization was 5261.6 kg/ha, and that of theoretical ethanol was 3078.0 L/ha. The application of simple sewage sludge led to an increase in conservative sugar yield (CSY) and theoretical ethanol yield (TEY) by 6.7–26.6% and reached 6664.3 kg/ha and 3895.6 L/ha, respectively (Figure 3).

The yield of conservative sugar in the SS + F treatment was 15.6–41.8% higher compared with that of the control and amounted to 6084.7–7459.2 kg/ha (CSY) and 3559.6–4363.6 L/ha (TEY).

Sorghum is a crop that actively absorbs and accumulates macronutrients. The introduction of sewage sludge intensifies this process. The nitrogen content in the aboveground biomass increased from 12–40% (dose of 20 t/ha) to 80–112% (dose of 60 t/ha), depending on the type and dose of sewage sludge (Table 3).

Potassium and phosphorus are also actively accumulated in sorghum biomass. The biogeochemical mobility coefficients (BGMC) of these elements are in the range of 10.9–13.2 (for potassium) and 3.9–5.7 (for phosphorus). The total amount of phosphorus in the aboveground sorghum biomass ranged from 0.024% in the control variant, and varied from

0.055–0.065% to 0.07–0.08% in the sewage sludge treatment. The total amount of potassium in the control was 0.226%. The content of this element increased slightly and amounted to 0.241–0.313% in experimental trials at doses of 20 t/ha and 40 t/ha. A dose of 60 t/ha led to the greatest effect when the content of potassium in the biomass increased by 80–94%.

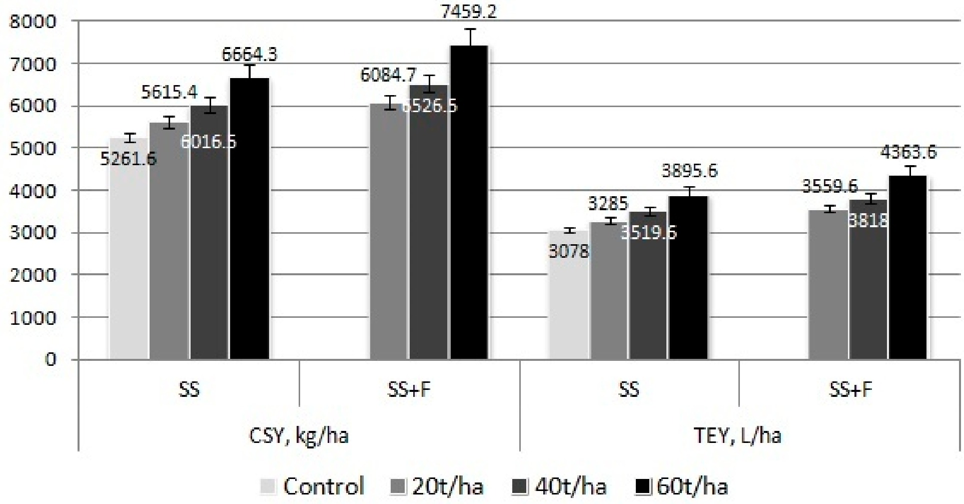

Figure 3. Yield of conservative sugar and theoretical ethanol depending on the type of sewage sludge and application rate.: CSY is conservative sugar yield; TEY is theoretical ethanol yield.

Table 3. Macronutrient content in sweet sorghum biomass.

Parameter	SS				SS + F		
	Control	20 t/ha	40 t/ha	60 t/ha	20 t/ha	40 t/ha	60 t/ha
Mass fraction of dry matter (%)	89.5 ± 1.61	89.6 ± 1.80	90.0 ± 2.11	89.6 ± 1.62	89.8 ± 1.69	90.0 ± 1.80	89.8 ± 1.53
Total nitrogen (%)	0.50 ± 0.13	0.70 ± 0.11	1.01 ± 0.10	1.06 ± 0.11	0.56 ± 0.14	0.78 ± 0.10	0.90 ± 0.10
Total phosphorus (%)	0.024 ± 0.004	0.065 ± 0.005	0.07 ± 0.006	0.09 ± 0.008	0.055 ± 0.005	0.06 ± 0.006	0.08 ± 0.007
Total potassium (%)	0.226 ± 0.06	0.241 ± 0.07	0.289 ± 0.09	0.439 ± 0.11	0.301 ± 0.09	0.313 ± 0.08	0.405 ± 0.09

The annual macronutrient uptake was calculated, taking into account the yield of fresh aboveground sweet sorghum biomass. The highest indicators were observed for nitrogen, and the lowest ones for phosphorus (Figure 4).

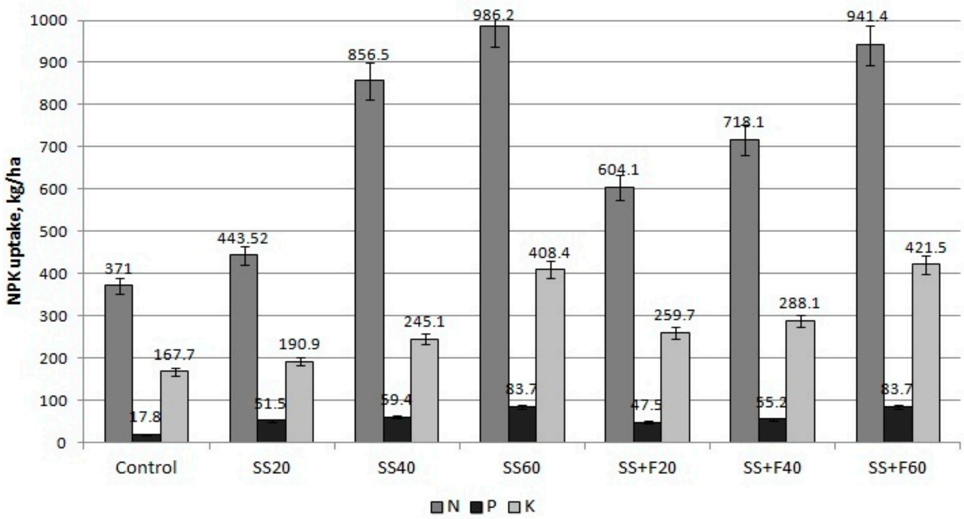

Figure 4. Macronutrient uptake by sweet sorghum biomass.

The application of sewage sludge contributed to an increase in the uptake of the macronutrients by sorghum biomass. The dynamics of the increase in the absorption of nitrogen and potassium in all trials of the experiment were identical. The smallest effect (from 13 to 60%) was observed in the SS20 and SS + F20 variants. The uptake of N and P in the treatments with a dose of 40 kg/ha increased by 1.5–2.3 times. The maximum absorption level was reached in the treatments with a rate of 60 t/ha and amounted to 250–265% of the control.

The effect of using sewage sludge on phosphorus uptake was the largest. This element uptake increased 2.7–2.9 times in the treatment with a dose of 20 kg/ha, 3.1–3.4 times in the trials with a dose of 40 kg/ha and 4.7 times in the trial with a dose of 60 kg/ha.

Among the studied trace elements, the amounts of iron, manganese and zinc in the aboveground sorghum biomass were the highest (Table 4).

Table 4. Content of trace elements in sorghum biomass (mg/kg).

Elements		**SS**			**SS + F**		
	Control	**20 t/ha**	**40 t/ha**	**60 t/ha**	**20 t/ha**	**40 t/ha**	**60 t/ha**
Fe	80.2 ± 2.11	107.3 ± 3.63	147.9 ± 3.80	199.7 ± 3.72	97.3 ± 2.51	111.7 ± 3.80	169.9 ± 3.84
Mn	50.2 ± 1.23	73.6 ± 1.81	85.3 ± 1.83	99.1 ± 1.95	62.6 ± 1.37	64.4 ± 1.42	72.4 ± 1.45
Cu	5.1 ± 0.40	6.38 ± 0.41	8.46 ± 0.51	12.36 ± 0.53	5.11 ± 0.38	6.41 ± 0.42	8.18 ± 0.48
Zn	35.4 ± 0.65	36.19 ± 0.67	54.28 ± 0.72	64.55 ± 0.76	39.70 ± 0.63	56.94 ± 0.70	60.86 ± 0.75
Co	0.11 ± 0.01	0.19 ± 0.01	0.30 ± 0.01	0.49 ± 0.02	0.14 ± 0.01	0.40 ± 0.01	0.46 ± 0.02
Ni	0.29 ± 0.02	0.42 ± 0.02	0.54 ± 0.02	0.61 ± 0.03	0.32 ± 0.02	0.40 ± 0.02	0.51 ± 0.02
Cr	0.06 ± 0.006	0.34 ± 0.01	0.63 ± 0.03	1.0 ± 0.11	0.30 ± 0.02	0.34 ± 0.02	0.76 ± 0.03
Pb	0.1 ± 0.008	1.18 ± 0.1	1.43 ± 0.04	1.71 ± 0.05	0.41 ± 0.02	0.94 ± 0.03	1.62 ± 0.06
Cd	0.01 ± 0.002	0.05 ± 0.003	0.06 ± 0.003	0.08 ± 0.004	0.03 ± 0.001	0.05 ± 0.002	0.06 ± 0.003

Zinc is the most actively absorbed element by sorghum plants. The values of the biogeochemical mobility coefficients in the control, SS + F20 and SS + F40 treatments varied within 12.2–13.4 in other trials of the experiment, namely 7.5–9.0. Iron is another actively accumulating micronutrient whose BGMC ranges from 6.9 (control) to 12.3 (SS60). Copper is the third most accumulative element, with its BGMC in the 4.0–5.8 range, peaking at 8.0 in the SS 60 treatment. Manganese is an element with an average accumulation index; its BGMC indexes do not exceed 1.5–2.3. The trend of accumulation of chromium by sorghum biomass in areas with sewage sludge application has been observed. The intensity of chromium accumulation was lower than that in the trial of SS + F, despite the fact that the content of this element in the biomass in the variants with simple sludge was higher. In the first case, the BGMC indicators did not exceed 1.1, while in the second case they were at a level of 1.7–2.5. The average absorption intensity of cobalt was noted in the SS40 + F and SS60 + F trials. The BGMC indices were in the range of 1.0–1.4. Nickel, cadmium and lead are not accumulated by sweet sorghum biomass even in trials with a high dose of sewage sludge. BGMC values were below 0.6–0.7.

The uptake of the main essential trace elements (iron, manganese, zinc and copper) ranged from several hundred grams to several kilograms, given the high yield of sweet sorghum, especially in the plots fertilized with sewage sludge (Figure 5).

The absorption of iron was the highest one and in the SS 60 and SS + F60 trials it was 18.6 and 17.8 kg/ha, respectively. The removal of manganese and zinc was also significant, with maximum values of 7.6–9.2 kg/ha (Mn) and 6.0–6.4 kg/ha (Zn).

The uptake of the heavy metals was small, no more than 100 g/ha (Figure 6). The cadmium uptake was the smallest: from 0.7 g/ha in the control plot, and to 6–7 g/ha in the plots with the introduction of sewage sludge. At the same time, lead uptake was the highest, reaching 120–170 g/ha in the SS40, SS60 and SS + F60 trials.

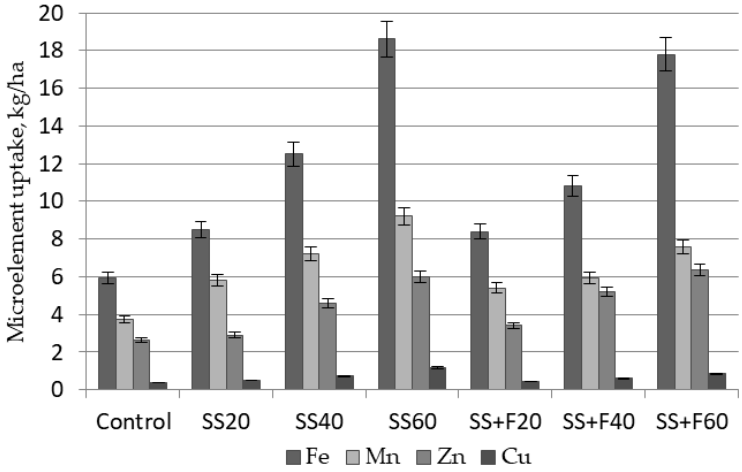

Figure 5. Essential trace elements uptake by sweet sorghum biomass.

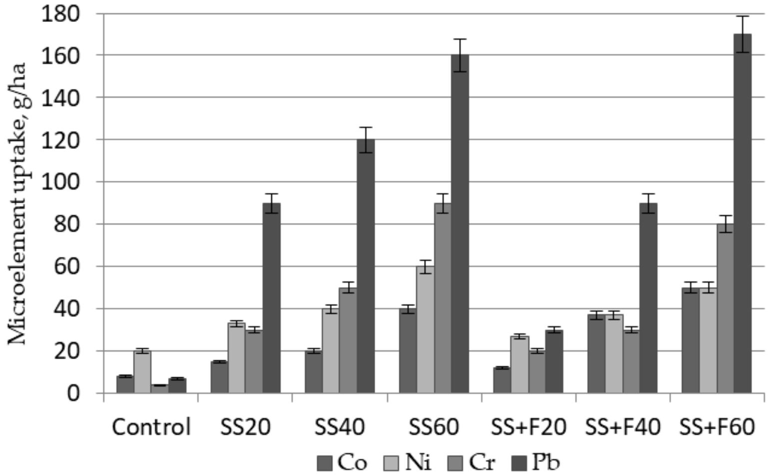

Figure 6. Heavy metal uptake by sweet sorghum biomass.

The thermal characteristics of dry biomass of sweet sorghum were analyzed to observe how the application of sewage sludge affects its properties during combustion. The main parameters of the destruction of sorghum biomass in different trials of the experiment are shown in Table 5.

Table 5. Main parameters of sorghum biomass thermal destruction.

Treatment	Stage	Interval (°C)	Peak (°C)	Maximum Rate (%/min)	Mass Loss (%)	Share of Residual Mass (%)
Control	I	30–170	110	5.3 ± 0.20	6.8 ± 0.22	3.6 ± 0.16
	II	170–420	390	40.0 ± 0.45	65.4 ± 0.54	
	III	420–600	460	7.6 ± 0.36	24.2 ± 0.43	
SS20	I	30–170	120	5.1 ± 0.18	5.4 ± 0.18	2.6 ± 0.13
	II	170–380	320	45.6 ± 0.48	60.8 ± 0.51	
	III	380–605	400	6.2 ± 0.21	31.2 ± 0.33	
SS40	I	30–180	130	8.1 ± 0.35	6.4 ± 0.18	1.9 ± 0.11
	II	180–410	300	53.2 ± 0.47	68.6 ± 0.59	
	III	410–600	440	6.9 ± 0.20	23.1 ± 0.39	
SS60	I	30–170	95	4.6 ± 0.18	4.9 ± 0.19	1.4 ± 0.09
	II	170–410	290	35.1 ± 0.46	65.8 ± 0.59	
	III	410–600	470	4.7 ± 0.18	27.9 ± 0.48	

Table 5. *Cont.*

Treatment	Stage	Interval (°C)	Peak (°C)	Maximum Rate (%/min)	Mass Loss (%)	Share of Residual Mass (%)
SS20 + F	I	30–170	95	5,0 ± 0.21	8,1 ± 0.25	1.2 ± 0.09
	II	170–400	290	44.6 ± 0.41	52.5 ± 0.46	
	III	400–600	440	4.3 ± 0.16	38.2 ± 0.41	
SS40 + F	I	30–160	80	5.5 ± 0.18	9.9 ± 0.19	1.1 ± 0.08
	II	160–390	290	50.8 ± 0.39	63.6 ± 0.58	
	III	390–600	450	5.2 ± 0.15	25.4 ± 0.47	
SS60 + F	I	30–150	95	5.1 ± 0.15	8.1 ± 0.16	1.1 ± 0.08
	II	150–410	280	45.6 ± 0.36	65.1 ± 0.68	
	III	410–600	470	7.1 ± 0.26	25.7 ± 0.45	

At the first stage of destruction, the thermal characteristics of sorghum biomass samples taken from plots treated with sewage sludge at a dose of 20 t/ha were identical to the control ones. The duration of the process of evaporation of water and volatile components and the rates of reactions were almost the same. Small differences in weight loss, as well as a shift of the peaks towards higher (SS20) or lower (SS + F20) temperatures, were observed. Pronounced differences in the nature of the decomposition of the main components of the biomass were recorded at the second stage (Figure 7).

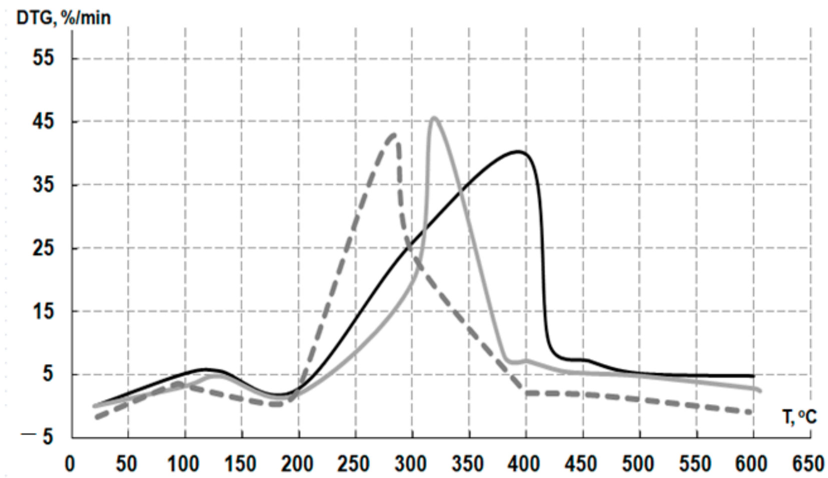

Figure 7. Thermal destruction of sweet sorghum biomass grown with the addition of sewage sludge (dose 20 t/ha). Black line, control; gray line, SS20; dotted line, SS + F20.

The main processes of thermal destruction of the biomass of sweet sorghum grown on plots with the introduction of sewage sludge took place at this stage in the range of lower temperatures than those in control samples. The speed of these processes was also higher. This is clearly observed in the steep thermogram curves. The weight loss in the test samples at this stage was 7.0–19.7% less than that in the control ones. The last stage of lignin decomposition and the formation of a fireproof residue took place more slowly in variants with sewage sludge. Sample combustion was more complete, especially in the SS20 + F trial. The weight loss was 28.9–57.8% more than that in the control. The application of sewage sludge at a dose of 40 t/ha had significant effects on the thermal behavior of sorghum biomass (Figure 8).

The SS40 trial was shifted to higher temperatures, and the SS + F40 trial shifted to lower temperatures at the initial stage of thermolysis, although the rates of the processes were identical in all variants of the experiment. The percentage of weight loss in the control and the SS40 treatment practically did not differ, and in the SS + F40 trial it was 45% more than that in the control. The stage of hemicellulose and cellulose decomposition was slightly shorter in the experimental samples, the rates of the processes were much higher (by 27.0–33.0%) and the degradation peaks were shifted to lower temperatures. The weight loss was almost constant in all three variants of the experiment. No special differences were found in the passage of the last stage of the thermal destruction of biomass. However, it was noted that the combustion of the prototypes was more complete. The proportion of residual mass was only 1.9% (SS40) and 1.1% (SS + F40).

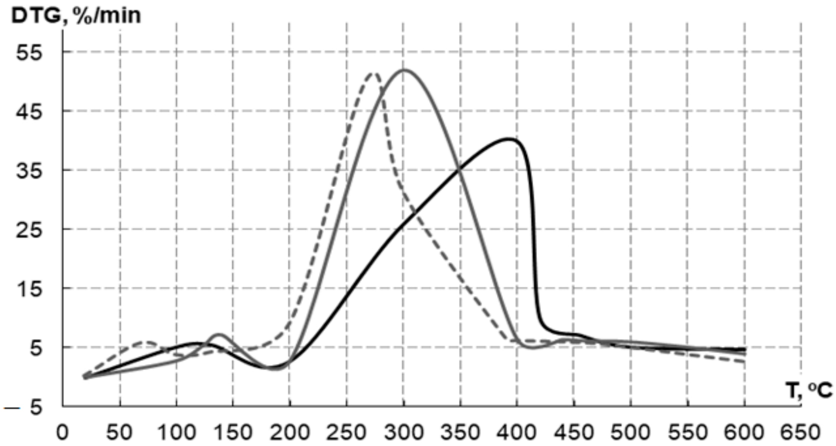

Figure 8. Thermal destruction of sweet sorghum biomass grown with the addition of sewage sludge (dose 40 t/ha). Black line–control, gray line–SS40, dotted line–SS40 + F.

There were also differences in the thermal characteristics of the experimental and control samples in the trial with the introduction of sewage sludge at a dose of 60 t/ha (Figure 9).

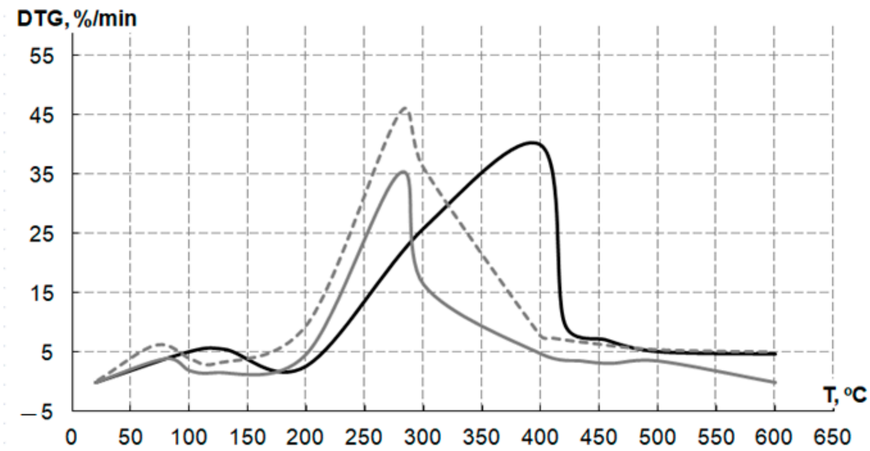

Figure 9. Thermal destruction of sorghum biomass grown with the addition of sewage sludge (dose 60 t/ha). Black line—control, gray line—SS60, dotted line—SS60 + F.

The degradation peaks in the test samples at the initial stage of decomposition of volatile components were shifted to lower temperatures, the weight loss in the SS60 trial was slightly less, and in the SS + F60 trial, slightly more than the control values. The processes of decomposition of the main components of the biomass in the test samples proceeded at lower temperatures than those in the control ones. However, the maximum rate of biomass decomposition in the SS60 trial reached only 35.1%/min, while in the SS + F60 trial it was the highest, at 45.6%/min. The nature of the passage of the last stage of destruction was similar in all variants of the experiment. However, in the SS60 treatment, the speed of the processes was lower. More complete combustion of the samples was observed in the SS + F60 trial.

4. Discussion

Sewage sludge contains significant levels of major nutrients (N, P, K), secondary nutrients (Ca, Mg, S) and micronutrients (Fe, Mn, Zn, Co) [63]. The content of toxic elements regulated in the fertilizer (As, Cd, Pb, Hg) depends on the sewage source.

We hypothesized that using municipal sewage sludge treated with DAMET flocculant can give several advantages in order to separate the solids from the water, and water solubilizes metals using gravitational force. Thus, decreasing heavy metal content in the sewage sludge treated with flocculant can be a guarantee of their low phytotoxicity and descent of intensity of biogeochemical absorption in the soil-plant system. In fact, the introduction of sewage sludge contributed to an increase in the uptake of the macronutrients by sorghum biomass. The level of absorption of nitrogen and potassium reached the maximum values in the variants with a dose of 60 t/ha and amounted to 250–265% of the control. The effect of the use of sewage sludge on the absorption of phosphorus was the greatest; the uptake of this element increased 2.7–2.9 times in the variants with a dose of 20 kg/ha, 3.1–3.4 in the variants with a dose of 40 kg/ha and 4.7 times in variants with a dose of 60 kg/ha.

The SS20 + F trial in our field experiments with sweet sorghum had relatively small effects on Zn, Cu and Pb content compared with other treatments. There were a couple of case studies to test different rates of sewage sludge on sweet sorghum yield and quality. A greenhouse experiment was conducted to quantify the effect of sewage sludge with doses of 16.0 and 32.0 Mg/ha [64]. The limed sludge slightly decreased soil Pb and slightly increased Cr and Zn soil concentration. The plant height and the biomass yield increased significantly with an increase in sewage sludge application in the field experiment with sorghum grown in heavy textured soil at the rate of 0, 25, 50 and 75 Mg/ha [65].

The newly reclaimed mudflats through sewage sludge amendment were used as a potential marginal land for bioenergy production studies to investigate the persistent impact of sewage sludge application at the rates of 0, 25, 50, 125 and 250 t/ha on selected soil physicochemical properties, yields and quality of sweet sorghum (*Sorghum bicolor* L.) cultivated in newly reclaimed mudflat saline-alkaline soil [66].

Although sewage sludge application led to the accumulation of heavy metals in sweet sorghum, the growth of sorghum was not inhibited even at the highest rate. Four doses of municipal sewage sludge (10, 20, 40 and 60 Mg DM/ha) were tested in other field experiments with sweet sorghum cultivated in Cambisol [1]. There were differences in the highest yield obtained for three varieties of sweet sorghum. It was also established that the content, uptake and index of the bioaccumulation of macronutrients and heavy metals contained in the sludge increased along with the increasing dose of the applied biosolids, reaching the maximum at 60 Mg DM/ha. The data obtained in the field experiment made in Cambisol coincided with our results obtained in such Technosols as phytomeliorated loess-like loam. Obviously, that low initial fertility of the phytomeliorated loess-like loam was not restricted with the highest rate (60 Mg DM/ha or 60 t/ha). At the same time, the main limitation is connected with highest uptake of heavy metals in the dose of 60 t/ha.

5. Conclusions

The application of a simple sewage sludge contributed to an increase in the humus content of 40–80% and the mass fraction of nitrogen from 22.9 to 59.5%, depending on the dose.

The yield of biomass depends on the dose of sewage sludge. When applying the maximum dose of 60 t/ha, productivity increases from 14.5 to 41.0%. In the same way, the content of conservative sugar and theoretical ethanol in fresh sorghum biomass increases. Depending on the dose and type of sewage sludge, the yield of sorghum grain increased from 6–15% to 34–60%.

Sorghum biomass actively absorbs nutrients from the soil. Nitrogen is absorbed most actively, and the introduction of sewage sludge increases the content of this element in plants. Depending on the type and dose of sewage sludge application, its content in biomass increased from 12–40% (dose 20 t/ha) to 80–112% (dose 60 t/ha). Potassium and phosphorus are also actively accumulated in sorghum biomass. The biogeochemical mobility coefficients of these elements are in the range of 10.9–13.2 (for potassium) and 3.9–5.7 (for phosphorus).

Among the essential elements, zinc experiences the most uptake by sorghum biomass. Other elements can be arranged in the following order: Fe → Cu → Mn.

The uptake of heavy metals by sorghum biomass was small, no more than 100 g/ha. The cadmium uptake was the smallest: from 0.7 g/ha in the control plot, to 6–7 g/ha in the plots with the introduction of sewage sludge.

Sewage sludge affects the process of thermal degradation of sorghum biomass. The decomposition of the main components occurs at lower temperatures, and, as a rule, at higher rates. Sewage sludge (especially treated with flocculant) contributes to a more complete combustion of biomass.

Considering the obtained results, it can be stated that sewage sludge with a flocculant at a dose of 40 t/ha is the most optimal fertilizer option for growing sweet sorghum for bioethanol and pellets on such Technosol as loess-like loam. Meanwhile, the final conclusion will be made over the next few years to see the after-effect of three rates on sweet sorghum yield and quality.

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References

1. Kołodziej, B.; Antonkiewicz, J.; Stachyra, M.; Bielińska, E.J.; Wiśniewski, J.; Luchowska, K.; Kwiatkowski, C. Use of sewage sludge in bioenergy production—A case study on the effects on sorghum biomass production. *Eur. J. Agron.* **2015**, *69*, 63–74. [CrossRef]
2. Melo, W.J.; Melo, G.M.P.; Melo, V.P.; Yada, M.M.; Carlos, R.S.; Silva, E.G. Sorghum growth in soil treated with sewage sludge from the textile industry. *WIT Trans. Ecol. Environ.* **2015**, *196*, 233–241. [CrossRef]
3. Shashoug, M.; Abdalla, M.; Elhadi, E.; Rezig, F. Response of fodder sorghum (*Sorghum bicolor* (L.) to sewage sludge treatment and irrigation intervals in a dryland condition. *Eurasian J. Soil Sci.* **2017**, *6*, 144–153. [CrossRef]
4. Cheng, H.; Hu, Y. Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. *Bioresour. Technol.* **2010**, *101*, 3816–3824. [CrossRef]
5. Kominko, H.; Gorazda, K.; Wzorek, Z. The possibility of organo-mineral fertilizer production from sewage sludge. *Waste Biomass Valorization* **2017**, *8*, 1781–1791. [CrossRef]
6. Przydatek, G.; Wota, A.K. Analysis of the comprehensive management of sewage sludge in Poland. *J. Mater. Cycles Waste Manag.* **2020**, *22*, 80–88. [CrossRef]
7. Glab, L.; Sowinski, J. Sustainable production of sweet sorghum as a bioenergy crop using biosolids taking into account greenhouse gas emissions. *Sustainability* **2019**, *11*, 3033. [CrossRef]
8. Maucieri, C.; Nicoletto, C.; Caruso, C.; Sambo, P.; Borin, M. Effects of digestate solid fraction fertilisation on yield and soil carbon dioxide emission in a horticulture succession. *Ital. J. Agron.* **2017**, *12*, 116–123. [CrossRef]
9. Singh, R.P.; Agrawal, M. Potential benefits and risks of land application of sewage sludge. *Waste Manag.* **2008**, *28*, 347–358. [CrossRef]
10. Kacprzak, M.; Neczaj, E.; Fijałkowski, K.; Grobelak, A.; Grosser, A.; Worwag, M.; Singh, B.R. Sewage sludge disposal strategies for sustainable development. *Environ. Res.* **2017**, *156*, 39–46. [CrossRef]

11. Ungureanu, N.; Vlăduț, V.; Voicu, G. Water scarcity and wastewater reuse in crop irrigation. *Sustainability* **2020**, *12*, 9055. [CrossRef]
12. Izydorczyk, G.; Mikula, K.; Skrzypczak, D.; Trzaska, K.; Witek-Krowiak, A.; Chojnacka, K. Agricultural and non-agricultural directions of bio-based sewage sludge valorization by chemical conditioning. *Environ. Sci. Pollut. Res.* **2021**, *28*, 47725–47740. [CrossRef] [PubMed]
13. Carrere, H.; Dumas, C.; Battimelli, A.; Batstone, D.J.; Delgenès, J.P.; Steyer, J.P.; Ferrer, I. Pretreatment methods to improve sludge anaerobic degradability: A review. *J. Hazard Mater.* **2010**, *183*, 1–15. [CrossRef]
14. Zhou, J.; Parker, W.; Laha, S. Biosolids and sludge management. *Water Environ. Res.* **2007**, *79*, 1496–1527. [CrossRef]
15. Malovanyy, M.; Shandrovych, V.; Malovanyy, A.; Polyuzhyn, I. Comparative analysis of the effectiveness of regulation of aeration depending on the quantitative characteristics of treated sewage water. *J. Chem.* **2016**, *2016*, 6874806. [CrossRef]
16. Di Bonito, M. Sewage sludge in Europe and in the UK. Environmental impact and improved standards for recycling and recovery to land. In *Environmental Geochemistry*; De Vivo, B., Belkin, H.E., Lima, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2008; pp. 251–286. [CrossRef]
17. Liang, Y.; Wang, R.; Sun, W.; Sun, Y. Advances in chemical conditioning of residual activated sludge in China. *Water* **2023**, *15*, 345. [CrossRef]
18. Getmanenko, V.A.; Skrylnyk, Y.V. Scientific-organizational and normative-legal aspects of recovery of sediments of communal sewage (on an instance of European experience). *Agrovisnyk* **2017**, *2*, 43–49. [CrossRef]
19. Dhar, B.R.; Nakhla, G.; Ray, M.B. Techno-economic evaluation of ultrasound and thermal pretreatments for enhanced anaerobic digestion of municipal waste activated sludge. *Waste Manag.* **2012**, *32*, 542–549. [CrossRef]
20. Liu, J.B.; Yu, D.W.; Zhang, J.; Yang, M.; Wang, Y.W.; Wei, Y.S.; Tong, J. Rheological properties of sewage sludge during enhanced anaerobic digestion with microwave-H_2O_2 pretreatment. *Water Res.* **2016**, *98*, 98–108. [CrossRef]
21. Ruiz-Hernando, M.; Simon, F.X.; Labanda, J.; Llorens, J. Effect of ultrasound, thermal and alkali treatments on the rheological profile and water distribution of waste activated sludge. *Chem. Eng. J.* **2014**, *255*, 14–22. [CrossRef]
22. Zhang, H.; Yang, J.K.; Yu, W.B.; Luo, S.; Peng, L.; Shen, X.X.; Shi, Y.F.; Zhang, S.N.; Song, J.; Ye, N.; et al. Mechanism of red mud combined with Fenton's reagent in sewage sludge conditioning. *Water Res.* **2014**, *59*, 239–247. [CrossRef] [PubMed]
23. Tyagi, V.K.; Lo, S.-L. Sludge: A waste or renewable source for energy and resources recovery? *Sustain. Energy Rev.* **2013**, *25*, 708–728. [CrossRef]
24. Devi, P.; Saroha, A.K. Utilization of sludge based adsorbents for the removal of various pollutants: A review. *Sci. Total Environ.* **2017**, *578*, 16–33. [CrossRef] [PubMed]
25. Svirenko, L.; Bondar, V. Sludge treatment for application in agriculture should be the option number one for Ukraine. *Linnaeus Eco-Tech* **2010**, *10*, 356–362. [CrossRef]
26. Vankovych, D.; Bota, O.; Malovanyy, M.; Odusha, M.; Tymchuk, I.; Sachnyk, I.; Shkvirko, O.; Garasymchuk, V. Assessment of the prospects of application of sewage sludge from lviv wastewater treatment plants for the purpose of conducting the biological reclamation. *J. Ecol. Eng.* **2021**, *22*, 134–143. [CrossRef]
27. Chernysh, Y.; Balintova, M.; Plyatsuk, L.; Holub, M.; Demcak, S. The Influence of phosphogypsum addition on phosphorus release in biochemical treatment of sewage sludge. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1269. [CrossRef] [PubMed]
28. Lopushnyak, V.; Hrytsulyak, H.; Voloshyn, Y.; Lopushniak, H.; Baran, B. Bioaccumulation and translocation of heavy metals in plants artichoke during sewage sediment in podzols soils. *EEET* **2022**, *23*, 178–187. [CrossRef]
29. Anbu Clemensis, A.C.; Martinez-Garcia, G.; Edyvean, R.G.J. Chemical precipitation of aerobically treated olive mill wastewater. *Desalin. Water Treat.* **2012**, *16*, 39–44. [CrossRef]
30. Meyn, T.; Altmann, J.; Leiknes, T. In-line coagulation prior to ceramic microfiltration for surface water treatment—Minimisation of flocculation pre-treatment. *Desalin. Water Treat.* **2012**, *42*, 163–176. [CrossRef]
31. Ștefan, V.; Simion, M.A.; Popa, L.; Nedelcu, A.; Ciupercă, R. Pre-treatment of industrial waste water with hydrocarbon separators. In Proceedings of the 18th International Scientific Conference Engineering for Rural Development, Jelgava, Latvia, 22–24 May 2019. [CrossRef]
32. Lee, C.S.; Robinson, J.; Chong, M.F. A review on application of flocculants in wastewater treatment. *Process Saf. Environ.* **2014**, *92*, 489–508. [CrossRef]
33. Yang, R.; Li, H.J.; Huang, W.; Yang, H.; Li, A.M. A review on chitosan-based flocculants and their applications in water treatment. *Water Res.* **2016**, *95*, 59–89. [CrossRef]
34. Bratby, J. *Coagulation and Flocculation in Water and Wastewater Treatment*, 3rd ed.; IWA Publishing: London, UK, 2016.
35. Chang, Q. *Flocculation in Water Treatment*, 2nd ed.; Chemical Industry Press: Beijing, China, 2011.
36. Wei, H.; Gao, B.; Ren, J.; Li, A.; Yang, H. Coagulation/flocculation in dewatering of sludge: A review. *Water Res.* **2018**, *143*, 608–631. [CrossRef]
37. Wang, X.; Chen, T.; Ge, Y.; Jia, Y. Studies on land application of sewage sludge and its limiting factors. *J. Hazard. Mater.* **2008**, *160*, 554–558. [CrossRef]
38. Hudcová, H.; Vymazal, J.; Rozkošný, M. Present restrictions of sewage sludge application in agriculture within the European Union. *Soil Water Res.* **2019**, *14*, 104–120. [CrossRef]
39. Moffat, A.J.; Armstrong, A.T.; Ockleston, J. The optimization of sewage sludge and effluent disposal on energy crops of short rotation hybrid poplar. *Biomass Bioenergy* **2001**, *20*, 161–169. [CrossRef]

40. Lag-Brotons, A.; Gómez, I.; Navarro-Pedreño, J.; Mayoral, A.M.; Curt, M.D. Sewage sludge compost use in bioenergy production—A case study on the effects on *Cynara cardunculus* L energy crop. *J. Clean Prod.* **2014**, *79*, 32–40. [CrossRef]
41. Gudulas, K.; Michailidou-Notara, P.; Notaras, E.; Papadimitriou, C.; Samaras, P. Management of Sludge from Municipal Wastewater Treatment Plants in the Regions of Thessaly and West Macedonia, Greece. In Proceedings of the International Conference on Environmental Management, Engineering, Planning and Economics, Skiathos, Greece, 24–28 June 2007; Kungolos, A., Aravossis, K., Karagiannidis, A., Samaras, P., Eds.; GRAFIMA: Belgrado, Serbia, 2007; pp. 1249–1254.
42. Golia, E.; Angelaki, A.; Giannoulis, K.; Skoufogianni, E.; Bartzialis, D.; Cavalaris, C.; Vleioras, S. Evaluation of soil properties, irrigation and solid waste application levels on Cu and Zn uptake by industrial hemp. *Agron. Res.* **2021**, *19*, 92–99. [CrossRef]
43. Choi, Y.H.; Moon, Y.H.; Ahn, S.H.; Yoon, Y.M.; Cha, Y.L.; Koo, B.C.; Kim, W.S. Characteristics of sweet sorghum germplasm for bioethanol production in reclaimed soil. *Korean J. Crop Sci.* **2012**, *57*, 384–388. [CrossRef]
44. Kim, S.; Ryu, J.H.; Paik, C.H.; Lee, S.H.; Oh, Y.Y.; Lee, J.T. Characteristics of emergence and growth of sorghum at various soil salinities and seeding methods in reclaimed soil. *Korean J. Crop Sci.* **2017**, *62*, 233–240.
45. Zhu, Y.; Song, X.; Wang, X.; Chen, W.; Niu, X. The yield increase and land improvement effects of different sorghum/wild soybean intercropping patterns on reclaimed coastal salt pans. *J. Soils Sediments* **2022**, *22*, 731–744. [CrossRef]
46. Dumitru, I.; Voicea, I.; Vlăduț, V.; Găgeanu, I.; Oprescu, R.; Persu, C.; Ungureanu, N.; Bălan, V. Technology for cultivating bicolor sorghum for food and energetic purposes. In Proceedings of the 7th International Conference on Thermal Equipment, Renewable Energy and Rural Development (TE-RE-RD), Drobeta Turnu Severin, Romania, 31 May–2 June 2018; pp. 239–244.
47. Caba, I.; Laza, E.; Vlăduț, V.; Marin, E.; Ungureanu, N.; Biriș, S.Ș.; Găgeanu, I.; Voicea, I.; Isticioaia, S.; Olan, M.; et al. Sweet sorghum—An alternative for Romanian farmers in the conditions of the current climate change. In Proceedings of the International Symposium ISB-INMATEH—Agricultural and Mechanical Engineering, Bucharest, Romania, 1–3 November 2018; pp. 945–954.
48. Nenciu, F.; Vlăduț, V. Studies on the perspectives of replacing the classic energy plants with Jerusalem artichoke and Sweet Sorghum, analyzing the impact on the conservation of ecosystems. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *635*, 012002. [CrossRef]
49. Sipos, B.; Réczey, J.; Somorai, Z. Sweet sorghum as feedstock for ethanol production: Enzymatic hydrolysis of steam-pretreated bagasse. *Appl. Biochem. Biotechnol.* **2009**, *153*, 151–162. [CrossRef]
50. Rakhmetov, D.B.; Vergun, O.; Blum, Y.B.; Rakhmetova, S.O.; Fishchenko, V.V. Biochemical composition of plant raw material of sweet sorghum (*Sorghum saccharatum* (L.) Moench) genotype. *Plants J.* **2018**, *79*, 83–90. [CrossRef]
51. Nghiem, N.P.; Toht, M.J. Pretreatment of sweet sorghum bagasse for ethanol production using Na_2CO_3 obtained by NaOH absorption of CO_2 generated in sweet sorghum juice ethanol fermentation. *Fermentation* **2019**, *5*, 91. [CrossRef]
52. Nenciu, F.; Paraschiv, M.; Kuncser, R.; Stan, C.; Cocârță, D.; Vlăduț, V. High-grade chemicals and biofuels produced from marginal lands using an integrated approach of alcoholic fermentation and pyrolysis of sweet sorghum biomass residues. *Sustainability* **2022**, *14*, 402. [CrossRef]
53. Akdeniz, H.; Yilmaz, I.; Bozkurt, M.A.; Keskin, B. The effects of sewage sludge and nitrogen applications on grain sorghum grown (*Sorghum vulgare* L.) in Van-Turkey. *Pol. J. Environ. Stud.* **2006**, *15*, 19–26.
54. Eid, E.M.; Shaltout, K.H.; Alamri, S.A.; Alrumman, S.A.; Hussain, A.A.; Sewelam, N.; Ragab, G.A. Monitored sewage sludge application improves soil quality, enhances plant growth, and provides evidence for metal remediation by *Sorghum bicolor* L. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 2325–2338. [CrossRef]
55. Börjesson, G.; Kätterer, T. Soil fertility effects of repeated application of sewage sludge in two 30-year-old field experiments. *Nutr. Cycl. Agroecosyst.* **2018**, *112*, 369–385. [CrossRef]
56. Kharytonov, M.M.; Martynova, N.V.; Babenko, M.G.; Rula, I.V. *Environmentally Compatible Utilization of Reclaimed Minelands for Sustainable Production Food and Bioenergy Feedstock*; Publishing House "Baltija Publishing": Riga, Latvia, 2020; pp. 625–658.
57. Kharytonov, M.M.; Gonchar, N.V.; Gavryushenko, O.O.; Mytsyk, O.O. Ecological Assessment of the State of Rocks in the of Reclamation Process in the Nikopol Manganese ore Basin. In *Resource-Saving Technologies of Raw-Material Base Development in Mineral Mining and Processing*; Universitas Publishing: Petroșani, Romania, 2020; pp. 392–413.
58. Dokuchaev Soil Institute. *Agrochemical Methods of Soil Investigation. Edited by USSR Academy of Science*, 4th ed.; Science Publishers: Moscow, Russia, 1965; 436p. (In Russian)
59. Ekefre, D.E.; Mahapatra, A.K.; Latimore, M., Jr.; Bellmer, D.D.; Jena, U.; Whitehead, G.J.; Williams, A.L. Evaluation of three cultivars of sweet sorghum as feedstocks for ethanol production in the Southeast United States. *Heliyon* **2017**, *3*, e00490. [CrossRef]
60. Thomas, R.L.; Sheard, R.W.; Mayer, J.R. Comparison of conventional and automated procedures for nitrogen, phosphorus and potassium analysis of plant material using a single digestion. *Agron. J.* **1967**, *59*, 240–243. [CrossRef]
61. Kharytonov, M.; Martynova, N.; Babenko, M.; Rula, I.; Gumentyk, M.; Bagorka, M.; Pashova, V. The production of biofuel feedstock on reclaimed lands based on sweet sorghum biomass. *Agric. For.* **2019**, *65*, 233–240. [CrossRef]
62. Kharytonov, M.; Martynova, N.; Babenko, M.; Honchar, N.; Sytnyk, S.; Sereda, V. Sweet sorghum cultivation in black soil and phytomeliorated rocks in Ukraine. *Acta Tech. Corviniensis-Bull. Eng.* **2021**, *14*, 103–106.
63. Boumalek, W.; Kettab, A.; Bensacia, N.; Bruzzoniti, M.C.; Othman, D.B.; Mandi, L.; Chabaca, M.N.; Benziada, S. Specification of sewage sludge arising from a domestic wastewater treatment plant for agricultural uses. *Desalin. Water Treat.* **2019**, *143*, 178–183. [CrossRef]
64. Arlo, L.; Beretta, A.; Szogi, A.; del Pino, A. Biomass production, metal and nutrient content in sorghum plants grown on soils amended with sewage sludge. *Helyon* **2022**, *8*, e08658. [CrossRef]

65. Al-Jaloud, A.A. Effect of sewage sludge on germination, growth and biomass yield of sorghum in calcareous soils. *Pak. J. Biol. Sci.* **1999**, *2*, 494–497. [CrossRef]
66. Zuo, W.; Gu, C.; Zhang, W.; Xu, K.; Wang, Y.; Bai, Y.; Dai, Q. Sewage sludge amendment improved soil properties and sweet sorghum yield and quality in a newly reclaimed mudflat land. *Sci. Total Environ.* **2019**, *654*, 541–549. [CrossRef]